INFLUENCE OF WINDSHEAR ON FLIGHT SAFETY

by

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1 INTRODUCTION

Wind shear during take-off and landing may crucially restrict flight safety. In some rare situations, especially during take-off, hazards may be caused by limited flight performance

In most cases wind shear accidents and incidents result from the fact that the wind shear phenomenon is not understood by the pilot due to his training condition and the cockpit instrumentation. In such situations the pilot is not able to act in the correct way. Therefore it can be suspected that a considerable amount of wind shear accidents will be interpreted wrongly as pilot's error.

Numerous investigations have been made in order to solve the wind shear problem. Many of these proposals will fail because the physical phenomena are not understood completely, neither by the pilots nor by the investigators of the wind shear warning system. This problem will be illuminated by the fact that some of the correct safety procedures in wind shear contradict the pilot's feeling of how to control an aircraft.

This paper tries to clarify step by step some physical backgrounds of the wind shear phenomena including adequate flight safety procedures to overcome the problems.

2. WIND SHEAR SCENARIO

Wind shear is an alteration of horizontal wind with time, height and distance. Concerning the airplane this results in a time varying wind speed.

Wind shear is not only related to stormy weather, as one might expect, but also to misty mornings in early summer as well as to bright sunshine in periods of fair weather [1]. In most cases wind shear is combined with up- and downdrafts.

Wind shear as a great variety of phenomena may be characterized by two extreme situations:

- thunderstorm with immense time varying effects, high turbulence and extreme downdrafts; (fig.1a)
- low level jet lasting for hours, no turbulence, less wind velocity outside the jet (fig.1b).

Between these two extremes several other kinds of wind shear related weather phenomena have been observed.

In addition flight safety may be reduced by wake turbulence caused by large buildings as well as by orographic lee effects. The effect of surface boundary layer is always persistent [2], (fig.2). Wake turbulence caused by large buildings (fig.3) can reduce flight safety as well as orographic lee effects (fig.4)

Due to geographic circumstances and the thickness of the shear layer, small or moderate wind shear gradients can be more dangerous in some exceptional situations than extreme thunderstorm shears [3].

3. AIRCRAFT RESPONSE DUE TO WIND SHEAR

The time varying wind changes first the airspeed of an aircraft due to its inertia. As a consequence varying aerodynamic forces accelerate the aircraft. Due to the static stability of the airplane and due to the pilot's behaviour to keep the airspeed constant, the aircraft will be accelerated by the varying wind. The airspeed deviation is amazingly small (fig.5). The largest airspeed deviation is caused by the dynamic response of the aircraft outside the shear layer [1]. The more important flight path deviations are demonstrated in fig.7 for take-off and in fig.6 for landing approach.

Investigations on energy transfer between wind and aircraft [1,4] have shown that energy based on inertial speed and height is fairly constant at small flight path angles. This is true for all transport aircraft in normal flight regimes (fig.5). Only glider aircraft can transfer significant energy from the wind in extreme flight manoeuvers, as for example in dynamic soaring flight. P.Krauspe [5] pointed out that wind shear induced by flight path deviations can be approximated by simple analytical functions (fig.8). A fundamental result of this investigation was that the aircraft response in wind shear is to a great extent independent of aircraft characteristics. The major parameters of influence are airspeed and lift to drag ratio. It should be noted that the earth-fixed wind shear can extensively modify the phugoid stability (fig.9). Krauspe's numerical calculations have been verified in a moving cockpit simulation. Fig.10, curve 1 shows the response of a wide body aircraft flown by an experienced airline pilot in a reported thunderstorm situation that caused the crash of a Boeing 727 in New York in 1975. Fig.10 delivers two essential answers:

- airspeed deviation is negligibly small even under adverse weather conditions (<10 kts);
- the pilot does not respond. The flight path is very similar to the fixed control situation in fig.8.

Fig.11 shows the response of the same aircraft in the same thunderstorm and downburst situation, when the aircraft is controlled by a less experienced airline pilot (1500 flight hours). The high control activity is typical but does not prevent the crash. The airspeed deviation is very low, too.

TAKE-OFF

The influence of wind shear on flight safety during take-off and go around differs very much from the situation during approach and landing. Handling qualities, cockpit instrumentation and training condition of the pilot are essential during landing approach. On the other hand limited flight performance, especially in a "one engine- out" situation of a twin-engined aircraft dominates during take-off, go around and missed approach. The typical response of an aircraft during take-off in a wind shear is illustrated in fig.7. Primarily dangerous is the strong reduction of flight path angle. The crash of a Continental Airlines Boeing 727 in Denver, Colorado in August 1975 in a thunderstorm is shown in fig.12 [3,9].Under the condition of a decreasing headwind that changed to an increasing tailwind coinciding with a strong downdraft, the aircraft struck the ground approximately 1 nm after lift off. This has been an accident that was unavoidable due to the severity of the wind shear encounter and the aircraft performing near its maximum capability.

OROGRAPHIC INFLUENCED WIND SHEAR

Less-known and understood is the potential hazard posed by low-velocity downdrafts and wind shear in the lee of a large-surface obstacle (fig.4). The influence of these factors has been studied at a German airport and with extensive simulation. The results of these studies follow.

The typical wind speed is given as V_W = 10 kt from 240° (fig.13). On the basis of this relatively low wind velocity, the wind model shown in figure 4 was developed. The different wind shear profiles result from the variable surface "roughness" of the area - (a neutral stability of the atmosphere was assumed). At higher wind speeds, additional eddies will take place but, with the present simulation model, these values are not sufficiently accurate [10]. The maximum downdraft velocity at a median west wind of V_W = 10 kt is 0.25 m/s.

The effect of orographic induced wind shear and downdraft is especially serious during take-off and missed approaches at airports, where the take-off and landing weight is limited due to runway length and obstacle clearance. This influence shall be demonstrated on a twin engined aircraft with an engine failure at the critical take-off speed V_1 or at the decision height.

For comparison, fig.14 shows the take-off and climb paths of a typical twin-engined medium-haul jet aircraft (A) and a typical twin-engined short-haul jet aircraft (B) in a case where second segment climb is hindered by an obstacle in the flight path. In this case, the flight path determines the maximum allowable take-off weight or, obstacle-limited take-off weight. The limited allowable take-off weight under these conditions is shown as a percentage of the aircraft's structural weight. Despite the different take-off weights and engine thrust the flight paths are essentially identical. From the standpoint of flight mechanics, the procedure can be described as "standard".

In the case of a limited take-off weight because of obstacles, the flight path is directly affected by the terrain and obstacles. In the case of a go around or a missed approach, however, the FAA does not stipulate a corresponding consideration of the terrain under the probable flight path. The rules here, assuming an engine failure, require only that a minimum climb gradient of 2,1% be maintained. Nevertheless, when the decision for a go-around is reached, obstacles within the missed approach area must be considered. In the event of an approach followed by a go around,where the engine failure occured prior to the beginning of the landing approach and the landing flaps have been set accordingly, it is assumed that the flight path always will be over areas known to be obstacle-free. If engine failure occurs at decision height while the aircraft is in a normal, both-engine landing configuration, it can (under certain circumstances) fly through the obstacle-free zone within the missed-approach area. The reason for the latter is the need of the aircrew to get the flaps from the "normal" landing position to the configuration for an engine-out balked landing. This takes time and has the effect of "stretching" the badly needed horizontal flight path for acceleration to a safe control speed or risking a loss of altitude. Despite identical points for the initiation of the missed-approach procedure, the performance characteristics of different aircraft result in different flight paths as shown in fig.15. Low-performance aircraft pose more of a problem.

This problem has been discussed for years in the International Civil Organization's (ICAO) Airworthiness Committee without any effect - so far - on airworthiness. Nor has the revision of the existing Procedures for Air Navigation Services - Aircraft Operations (PANS-OPS) brought any progress in this context. The new PANS-OPS contain, among other things, new and modified methods for the determination of obstacle-free criteria. The directives are based upon results achieved with the help of scientific methods including a Collision Risk Model (CRM) which can estimate the risk of a collision with obstacles under given marginal conditions. The computer model will be put at the disposal of the ICAO member States. The method, however, does not include such "extraordinary" factors as wind shear or turbulence.

A special hazard to flight safety during both take-off and go around can be created when climb capability is degraded by unfavourable wind conditions. Wind has a direct influence on the flight path and, as a result, on the obstacle clearance height. Wind also is a key factor in computing the maximum allowable take-off weight.

Wind speed and direction depend upon both position and time. In other words, the wind factor is a continuous variable affecting an aircraft's flight path. The resulting aircraft dynamics can be computed only with the aid of a costly simulator. To simplify the take-off procedure, the wind is considered to be constant. This relative wind velocity is measured at the surface and a median speed is an average over the last 10 minutes. As far as wind speed for take-off is concerned, the FAA requires that headwinds be calculated at 50% of the nominal value, and performance-decreasing tailwinds considered at 150%.

In "worst-case" situations, the variation between the actual wind conditions and the reported median can be as high as 80%. Wind shear and updrafts or downdrafts are not included in take-off computations despite their effect on the climb-out flight path. The reasons for this is the current lack of measuring capabilities and the long-standing assumption that the vertical wind components near the surface are so small they may be ignored.

Fig.16 shows gross and net flight paths for a wind simulation as indicated in fig.4. (The corresponding flight paths under no-wind conditions are shown in fig.14) The strong influence on flight path displacement even with a relatively low headwind of V_W = 10 kt is quite pronounced. Both aircraft A and aircraft B are well below the 10,7 m minimum clearance height even though, according to the regulations, only 50% of the headwind component is used to compute take-off weight. Without the influence of wind shear and downdrafts, the actual overflight altitude would be much higher than the minimum allowable overflight altitude due to the 50% "risk" factor. But the result is that the 50% "safety" factor, in the given wind model, is completely used up. In the often-underestimated "lee influence", the low flight path under engine-out conditions can be wiped out by a downdraft velocity of 0.12 m/s despite the improved climb performance provided by a headwind of 10 kt. Additional air recirculation or variations in the measured wind speeds would reduce obstacle-clearance even more.

Despite the relatively comparable take-off performance of the two hypothetical aircraft (fig.14), the two aircraft have very different flight paths under the wind conditions studied (fig.16). The reason is in the dynamic reaction of the aircraft to the variable wind conditions. An important parameter here is the thrust radius - the geometric distance between the engines and the aircraft's center of gravity (CG) - and the relationship between the thrust available and airspeed. A study of other twin-engine aircraft indicates that the farther below the CG the engines are mounted, the stronger and, in general, less favorable are the aircraft's dynamic reactions in its flight path. This "problem", however, should not be overestimated in a discussion of obstacle clearances.

For low-performance aircraft, a one-engine go around can be far more critical than a take-off (fig.17). Under the wind parameters shown in fig.4, aircraft B would hit the obstacle. Under still-air conditions, the clearance height would be marginal, but would meet regulations.

4. OPERATIONAL CONSIDERATIONS TO PREVENT WIND SHEAR ACCIDENTS

As the response of a piloted aircraft differs very much during approach and landing and on the other hand during take-off and go around, the procedures for accident prevention are quite different.

TAKE-OFF

A trivial but powerful advise would be: don't start under thunderstorm conditions. The probability to survive is small in strong thunderstorms during take-off.

The inclusion of wind shear considerations excluding thunderstorms in take-off and go around regulations makes sense only when related to specific obstacle conditions and when certain weather situations can be predicted with some probability. It also would be necessary to compute, with a simulator, the actual situation. The simulation model would have to include actual wind values as measured at the airport in question. This technique could be supported by information to pilots that certain wind situations could occur at certain airports and the pilots should be alert for such possibilities. At new airports, another possibility would be the consideration of the statistical distribution of the main wind directions as well as of the surrounding terrain's effect on the wind. Existing airports could be modified to minimize any restrictions on flight operations.

The reduction of flight weight to provide a great margin of safety for take-off and go around - especially in the case of unforeseen wind shear - is an economic factor which no one regards with pleasure. For take-off, it has been shown that the 50% headwind factor provided by the FARs can be completely consumed under the conditions of the hypothetical wind model presented here. Other areas such as inexact wind velocity measurements and time-variable winds cannot be covered by the 50% safety factor. It would seem here, that an increased take-off weight due to a headwind component should not be allowed under the conditions described. It has been shown that the FARs for go around procedures impose far lower requirements than for take-off. This is most likely based upon the fact that, when a go around decision is made, the altitude and course already exist and the process is somewhat less critical.

If, however, an engine failure is assumed at go around decision height - similar to the V_1 decision speed at take-off - the flight distance required to reach a safe climb speed is quite long. In this case the FARs should require that gross flight paths for go arounds under the marginal conditions noted above should be computed and, as for the net flight path, provide a minimum obstacle clearance of 10.7 m in the "Balked Landing" sector. It is admitted that, according to the examples given, the authorized maximum landing weight would be reduced considerably, but a safety minimum would be guaranteed

LANDING APPROACH

In contrast to take-off and go around accidents, wind shear accidents during approach and landing could generally be avoided, if the pilot or the automatic flight control system reacts in a correct manner. In all approach wind shear accidents, analyzed by the author, neither limited flight performance nor slow engine response time, nor exclusively non-adequate control of elevator and thrust were the basic reason for the crash.

As mentioned in chapter 3, the total energy of an uncontrolled aircraft in a wind shear situation is nearly constant, the airspeed deviations are negligibly small and the aircraft will be accelerated without significant time delay with the time varying wind. The main deviation occurs on the flight path. In case of an increasing tailwind, the aircraft would be accelerated inertially and this will increase the kinetic energy. If the total energy is constant the potential energy and therefore the height has to decrease. From this unexpected aircraft response results:

- pilot and automatic flight control system can neither indicate a wind shear situation from airspeed deviation nor from criteria based on total energy deviation;
- a powerful wind shear indication is the deviation from the glide path.

It can be assumed that flight safety will be guaranteed in a wind shear situation if airspeed and flight path deviations are small. In this case additional thrust will be required to accelerate the aircraft without flight path deviation.

The required thrust or specific excess power $\dot{H}_E$ to avoid airspeed and flight path deviations is shown in fig.18 curve R for the wind shear gradient of fig.5.

Today's flight control systems based on the classical concept of separating autopilot and autothrottle can already reduce the hazards of wind shear to a considerable amount. In fig.18, curve A, the throttle activities of such an automatic control system of a European wide-body aircraft is given in the above mentioned linear tailwind shear.

A comparison with the required values (curve R) reveals that this modern flight guidance and control system executes principally correct compensations.

The excursions in the airspeed and flight path signals originate from the special flight control structure. A high throttle activity as a response to higher frequency gusts is avoided here by means of a complementary filtering technique. This brings the disadvantage of a delayed counteraction against the low frequency wind shear disturbances only after relatively great offsets of airspeed and flight path have established.

The employment of stronger cross-coupled flight control systems, no longer separated into autopilot and autothrottle and operating on the basis of an energy management [14]leads to a further considerable reduction of the total energy excursions while using conventional sensoring.

By means of an additional direct open-loop compensation the offsets in airspeed and flight path caused by wind shear can be eliminated almost entirely [11]. This method is based on the on-board measurement of the wind vector components and their time derivatives and a corresponding thrust command signal. In this way an ideal thrust signal in wind shear is generated (see fig.18, curve R) without changing the original stability of the controlled aircraft. Two main disadvantages have to be noted, however: first, complete airdata and inertial data must be available on board the aircraft in order to determine the wind components. Secondly, the above mentioned complementary filtering of the wind signal can no longer be maintained because it would counteract the open-loop activation of the thrust due to its structural composition. This method cannot be employed successfully until the problem of separating the wind shear and gust signals has been solved completely.

A management of the aircraft's energy and energy rate (based on airspeed) leads despite its simple structure to very small deviations of the airspeed and height. The concept for such a flight control system can be derived from the following principle: The required thrust is proportional to the deviation in specific excess power $\tilde{\dot{H}}_E$, and the time integral of $\tilde{\dot{H}}_E$, the energy height error $\Delta\tilde{H}_E$, is an indication of the total energy state of the aircraft [1]. The specific energy rate deviation can be calculated simply by a linearized approximation:

$$\Delta\tilde{\dot{H}}_E = - \frac{V \dot{V}}{g} + V \Delta\gamma + \gamma \Delta V$$

with: V airspeed

γ flight path angle

Δ deviation

• time derivative.

In order to determine this equation, no expensive measurement is necessary. It is sufficient to combine existing sensor signals. Curve B in fig.18 shows the answer of the specific energy rate and the corresponding state of flight variables when the principle of the total energy rate management is applied. The unimportant deviations of the airspeed and height are substantially referred to the influences of engine ime delays. Nevertheless, filtering of the V- and $\dot{V}$-signals is still necessary in order to prevent the thrust from following each gust.

Great difficulties for pilots occur in downdraft or downburst situations. To maintain flight safety the pilot should keep angle of attack, airspeed, and flight path angle constant. In case of a downdraft the pilot has to pull the control column in order to increase the aircraft's pitch angle [14]. The procedure to pitch up the aircraft in a situation, where the airspeed decreases (although only slightly), is adverse to the pilots feeling and training. As downdraft counteraction isn't generally implied in most flight director control laws, the pilot tries to keep the pitch angle constant with the result of an undesired flight path deviation. Therefore pilots should be trained to react adequately in downdraft situations.

WIND SHEAR WARNING DISPLAY

Concerning the prevention of wind shear accidents the major problem which has to be solved is to inform the pilot in a proper manner about his situation. In principle all sensor signals the pilot needs for a proper information are available in the conventional cockpit instrumentation. Even in well equipped wide body aircraft the pilot is not yet able to correlate all of these informations in order to realize a correct warning.

Wind shear can be described by characteristic values, of the shear gradients, the thickness of the shear layer or the overall shape of the wind changes. On board the aircraft only the momentary wind gradients can be determined. But note that in contrary to the opinion among experts [13] the gradients alone are no exclusive measure for the hazard. No forecast of the expected total event of the wind shear can be given based only on the knowledge of the momentary wind shear gradients. And there is yet no evidence that an aircraft is more endangered by a high wind gradient, lasting only a short time, than by a small but persistent gradient which is possibly not recognized by the pilot. A better means for evaluating the threat of a wind shear to the aircraft appears to be an energy height error. As far as we could investigate, energy height errors of the magnitude of 15 to 20 meters (resp. kinetic energy errors of around 2.5 m/s) may be tolerated at higher altitudes during take-off and landing. However, the allowable errors have to be obviously narrowed with decreasing height of the aircraft above the ground. To avoid uncomfortable and unnecessary miswarnings, the pilot should not be warned until these limits are violated.

It appears difficult to supply the pilot with another information in view of the great burden of control task he has in a landing approach. The question arises whether to install additional instruments or to modify already existing displays. This is more or less a question of philosophy that is certainly going to answer itself when new or modified instruments fulfil the one and only requirement: They must display the proper quantity that will only warn the pilot when it is necessary, and that will give him appropriate guidance when he needs it.

The concept of displaying airspeed based on energy and energy rate [1] (chapter 4) has been tested in a moving cockpit simulator by a joint team of Bodenseew rk Gerätetechnik, Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt (DFVLR) and Technical

University Braunschweig. This research was sponsored by the German Ministry of Transportation (BMV) [6]. Fourteen airline pilots flew different approaches, where the New York thunderstorm profile [7] (fig.10,11) caused the heaviest problems. In the absence of additional aircraft systems, e.g. autopilot wind shear warning, none of the well motivated pilots were able to land the simulated wide body aircraft without a crash, even though the response o. experienced pilots was different from less experienced pilots. (curve 1, fig.10,11)

With the display of energy and energy rate, most of the pilots recovered in a hard but safe landing (fig.10,11, curve 2). During these simulator studies the questions arose, if it is worthwhile to display energy and energy rate in different instruments or to combine both signals in one display [12]. This question shall be answered in an additional simulator study, where man-machine problems will be optimized. The main results of the simulator studies were:

- pilots (both well or less experienced) are not able to make a safe landing under severe wind shear conditions without additional support of an automatic flight control system or an adequate wind shear warning display;
- if there is enough training available, pilots can adapt themselves to specific wind shear profiles. It is therefore necessary to expose the pilot to different wind shear situations. A general ground based wind shear warning is worthwhile but not sufficient;
- an adequate wind shear warning display can support the pilot in the most severe wind shear situations.

5. CONCLUSIONS

Wind shear during take-off, go around, and missed approach is a pure flight performance problem. Pilots should avoid to take off into thunderstorms. Moderate wind shear induced by orographic lee effects can be overcome by increasing the thrust to weight ratio, especially in engine failure conditions. In unexpected dangerous situations the pilot is advised to reduce the airspeed safety margin in order to increase the obstacle clearance. Wind shear accidents during landing and approach could generally be avoided if the pilot keeps the automatic flight control systems in operation and if he is informed by an adequate wind shear warning display. Wind shear is particularly dangerous if it occurs in a height of approximately 80-120 m.

A ground based wind shear warning is worthwhile but not sufficient. The adequate information of the aircraft response in wind shear can only be measured on board. A major parameter is airspeed; high airspeed leads to greater flight path deviation.

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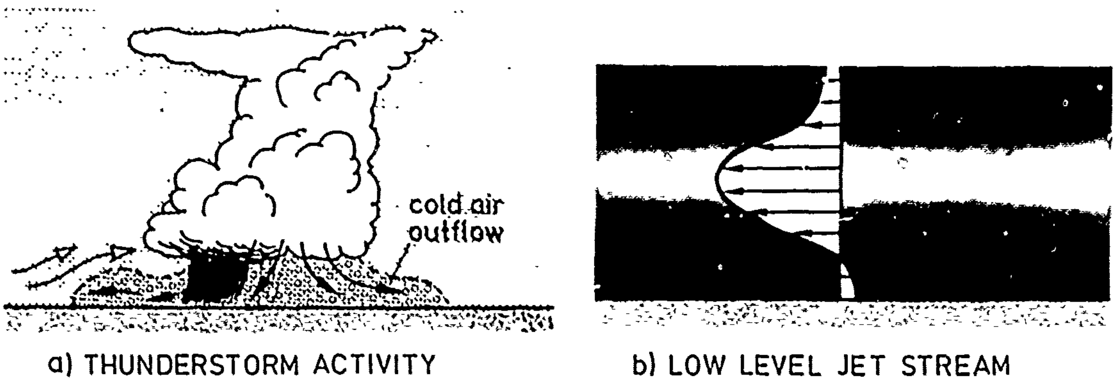

Fig. 1: Meteorological Scenario significant for wind shear conditions. [1]

AIRPORT	:WIEN
DATE	:7.2.82
TIME	:16:46 GMT
RUNWAY	:30
SURFACE WIND(*)	:7,0 m/s / 280°

*METAR

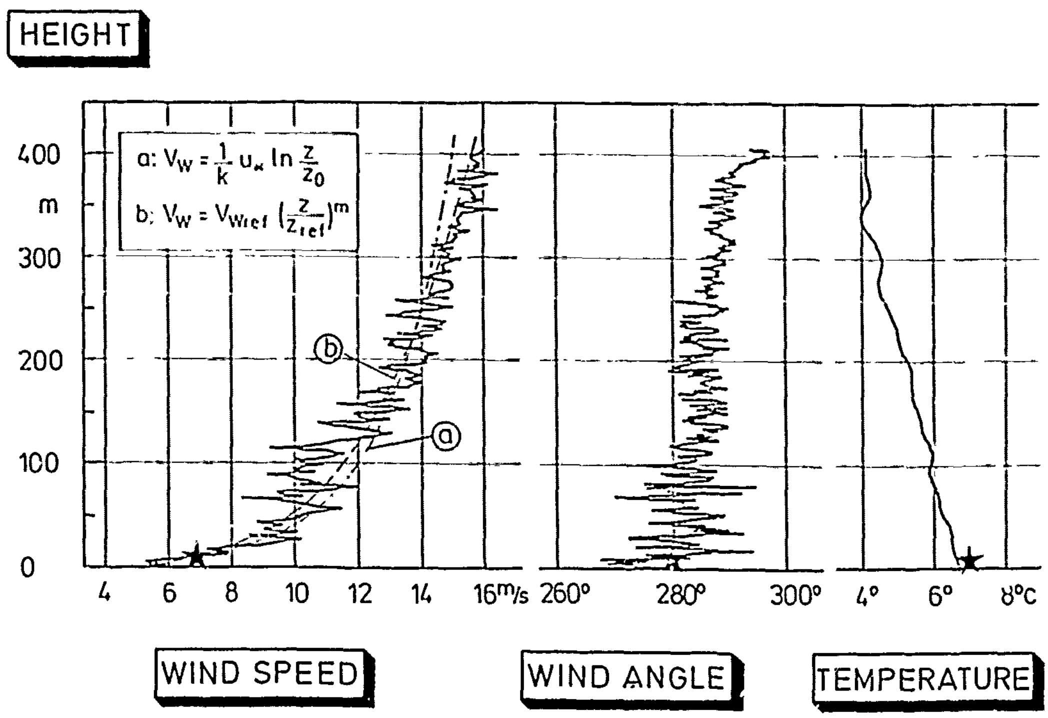

Fig. 2: Example of a typical boundary layer wind profile.

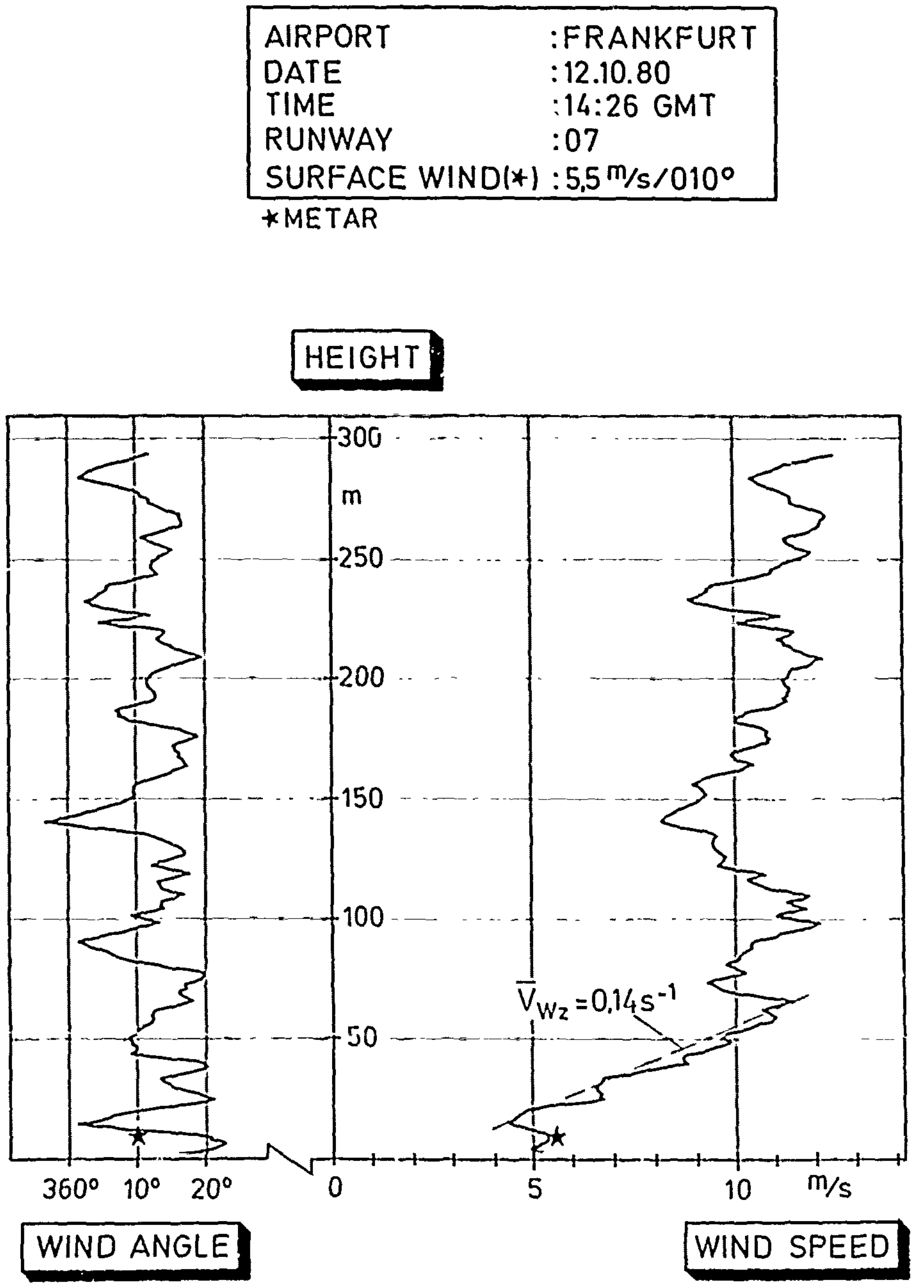

Fig. 3: Sample wind shear profile

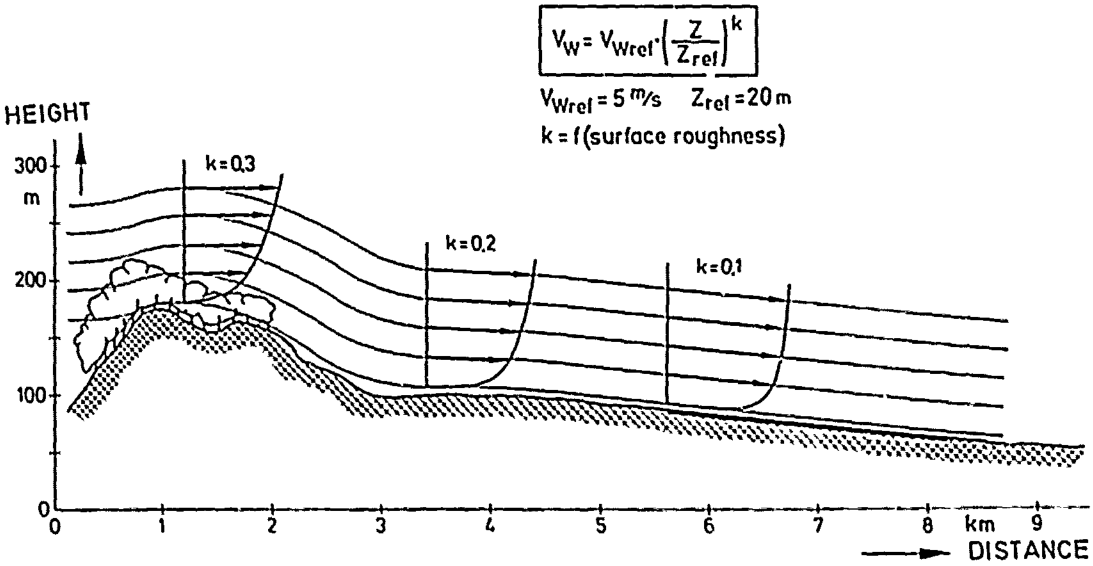

Fig. 4: Model of windstream lines and profiles over a mountain ridge [3]

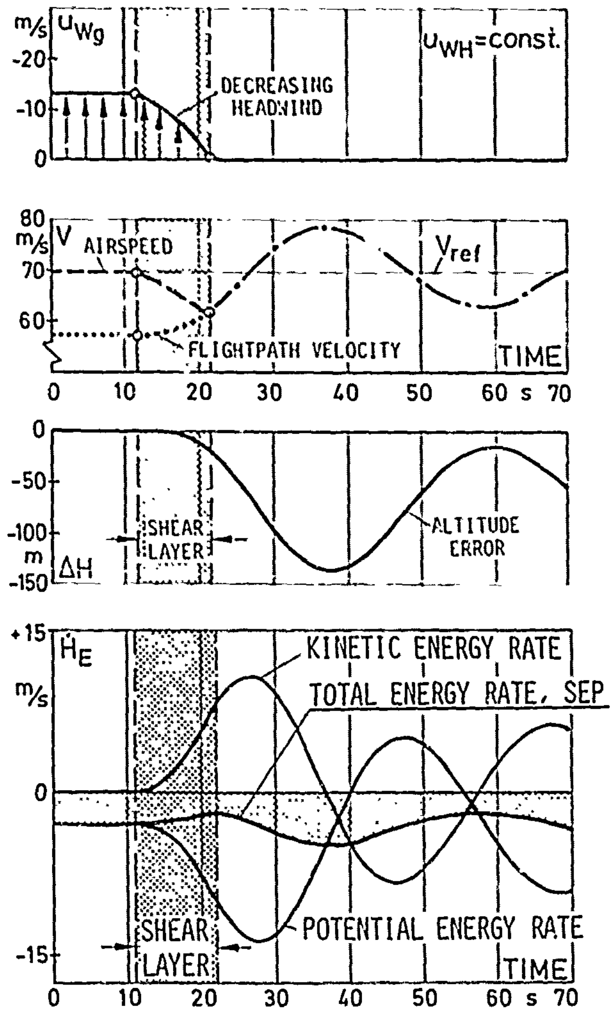

Fig. 5: Effect of tailwind shear on velocities, altitude and energy deviation.

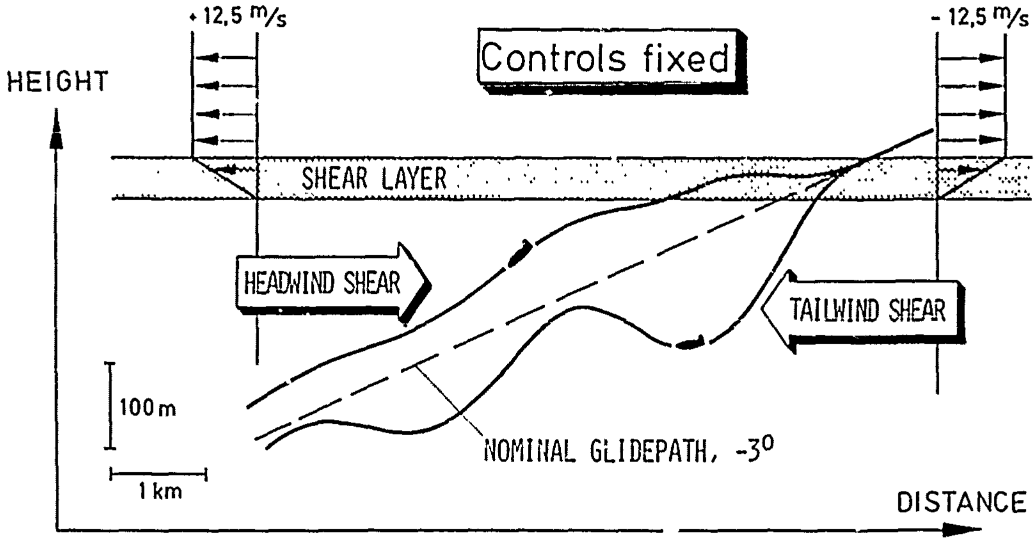

Fig. 6: Landing approaches in headwind resp. tailwind shear, controls fixed [1]

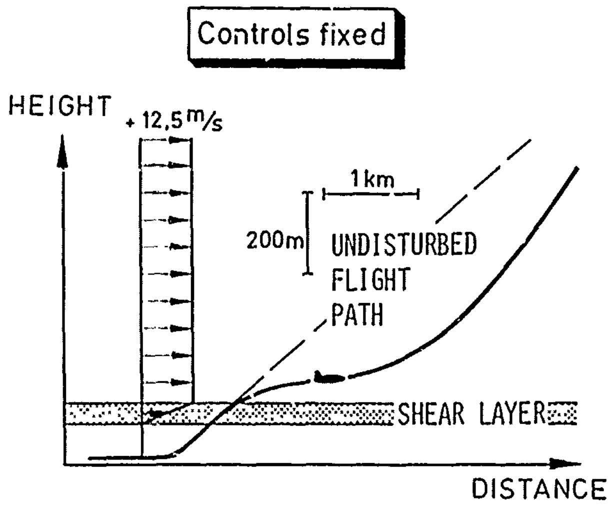

Fig. 7: Take-off flight path in tailwind shear, controls fixed [1]

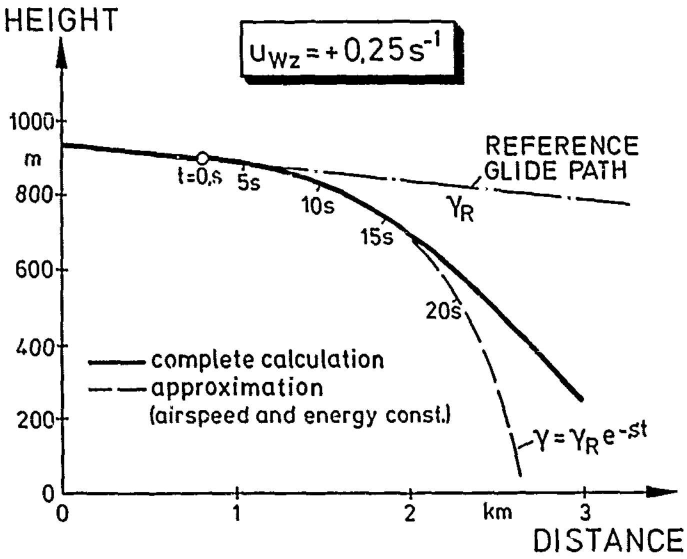

Fig. 8: Flight path of an aircraft with fixed controls in a constant vertical wind shear gradient u_{Wz} [5] (s = Eigenvalue of phugoid mode, see fig. 9)

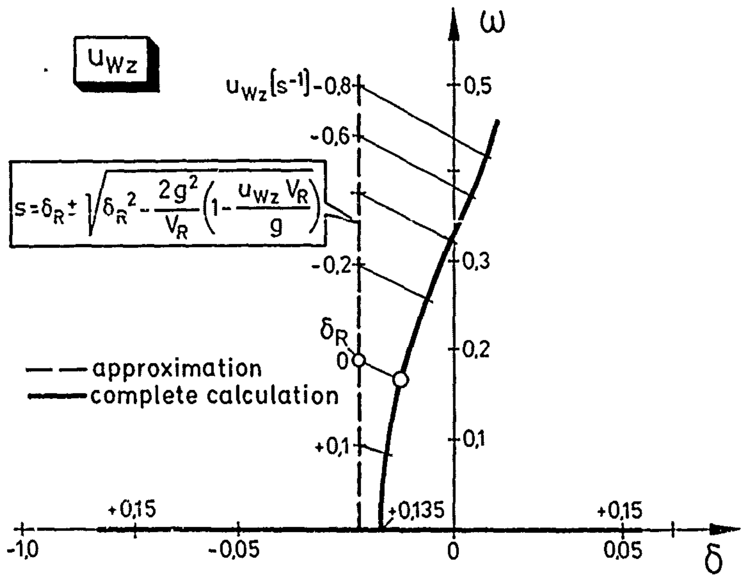

Fig. 9: Eigenvalues of the phugoid mode as a function of a constant vertical wind shear gradient u_{Wz} [5] (Index R: Referencedata)

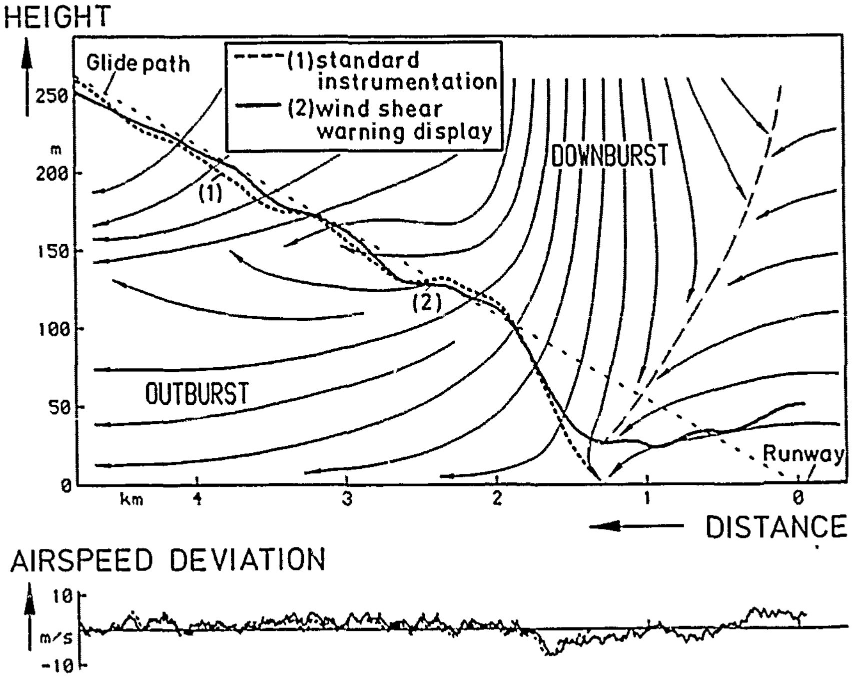

Fig. 10: Flight simulator approach in wind shear conditions, experienced airline pilot

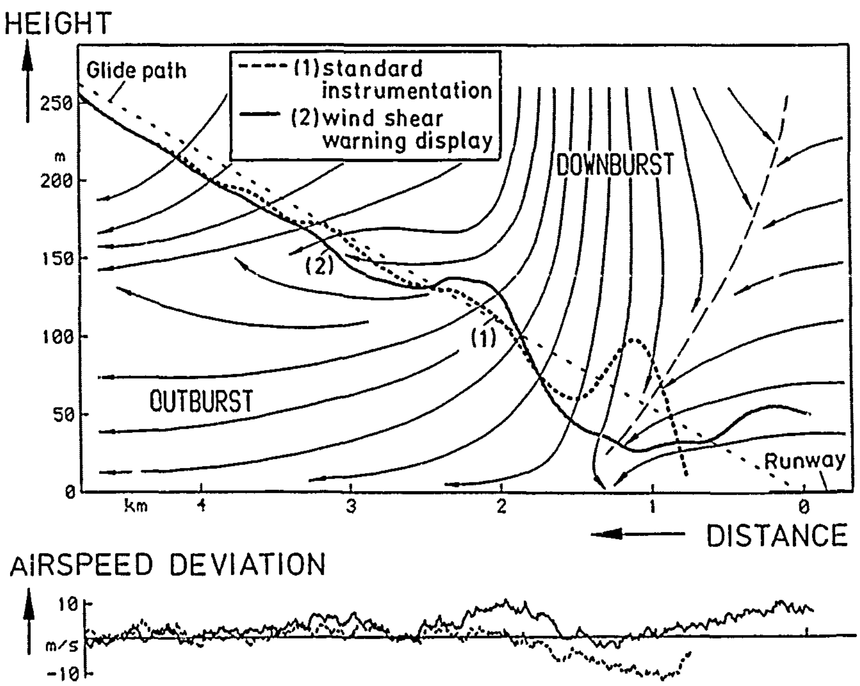

Fig. 11: Flight simulator approach in wind shear conditions, less experienced airline pilot

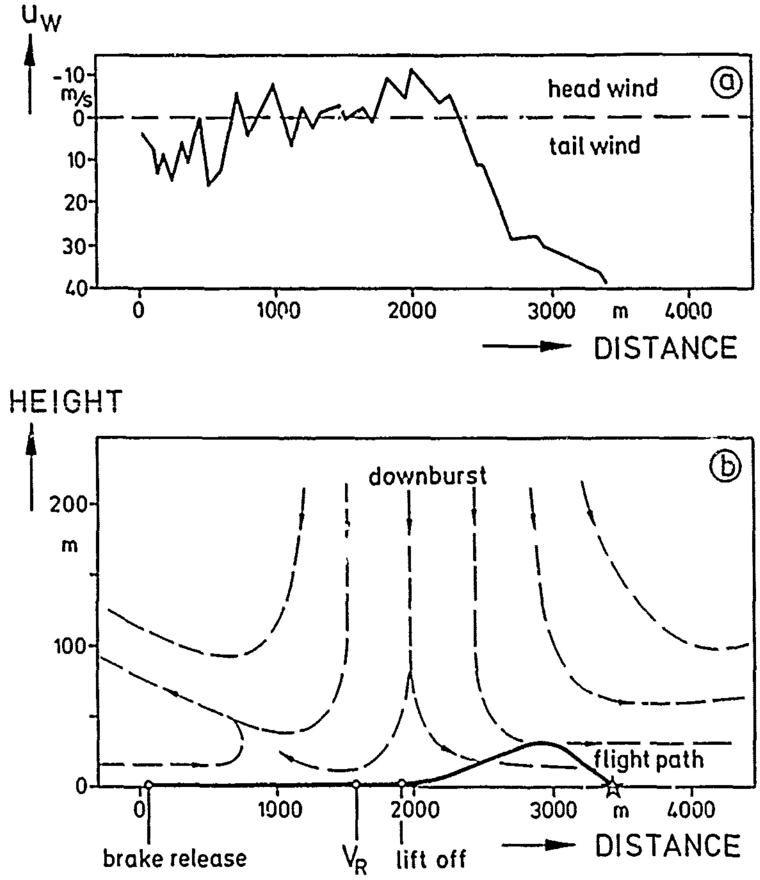

Fig. 12: Analyses of wind shear effect in an aircraft takeoff accident:
a) Horizontal wind component along the flight path; b) Reconstructed traces of windstream lines and aircraft flight path [9]

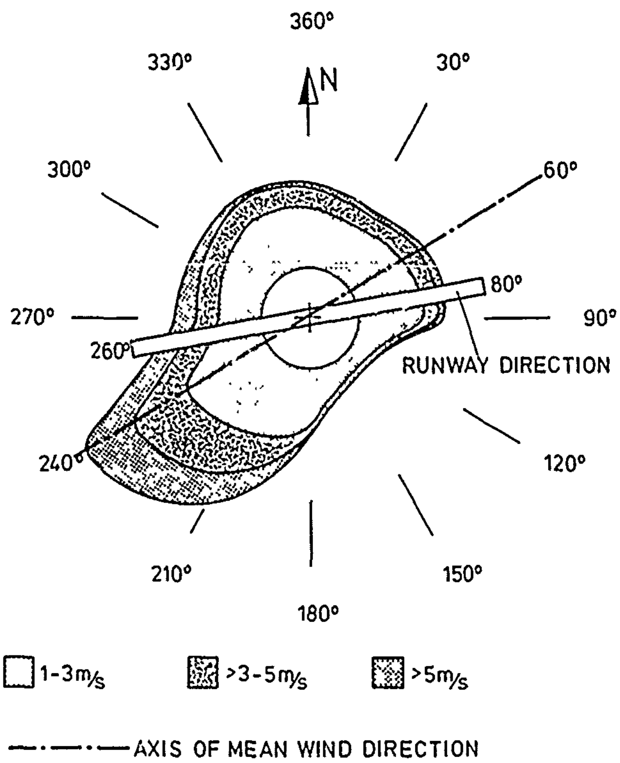

Fig. 13: Annual mean wind distribution of a specific German airport [3]

	take-off weight		
	structure [to]	maximum [to]	limitation [%]
A	137,0	132,0	-3,7
B	50,3	45,1	-10,3

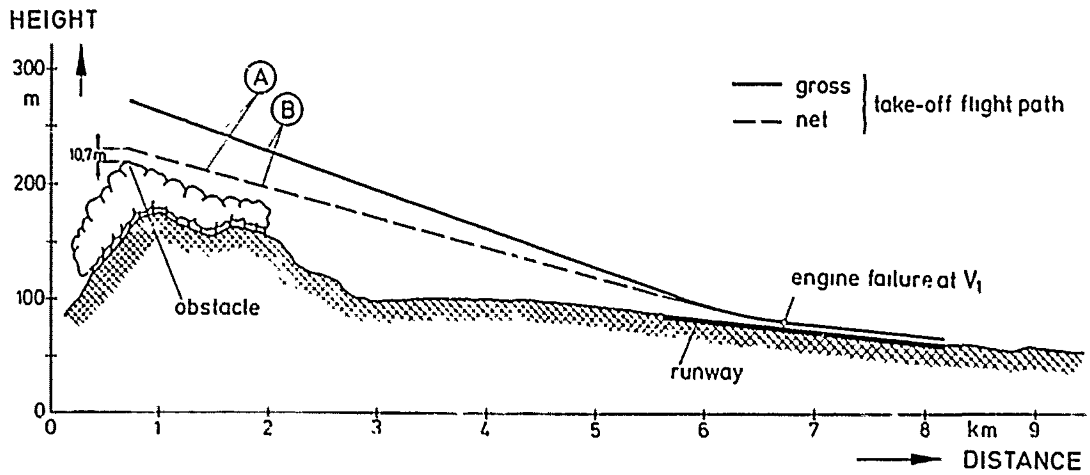

Fig. 14: Takeoff flight paths of two twin-engined jet aircraft under conditions of obstacle-limited takeoff weights and an engine failure at V_1 [3]

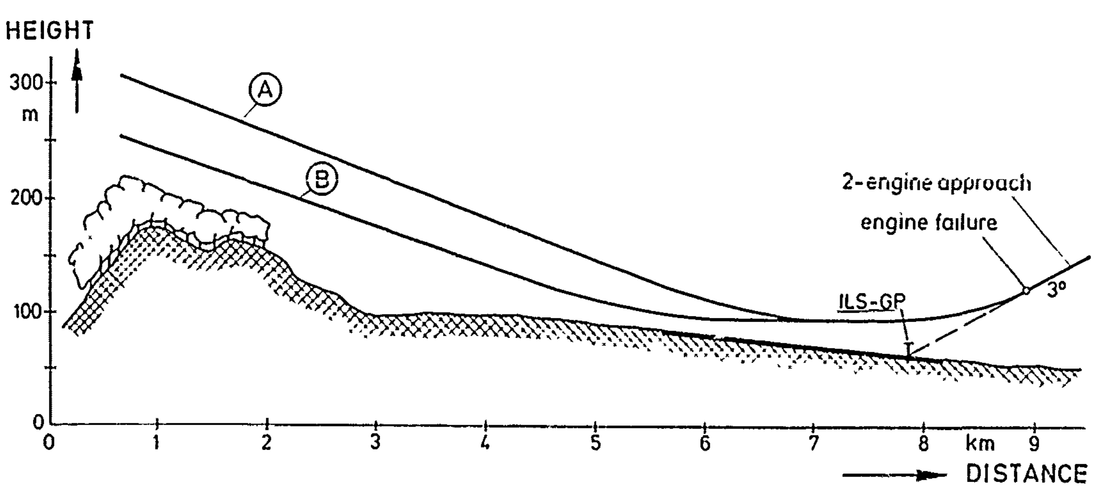

Fig. 15: Go-around flight paths of different aircraft at maximum allowable landing weights [3]

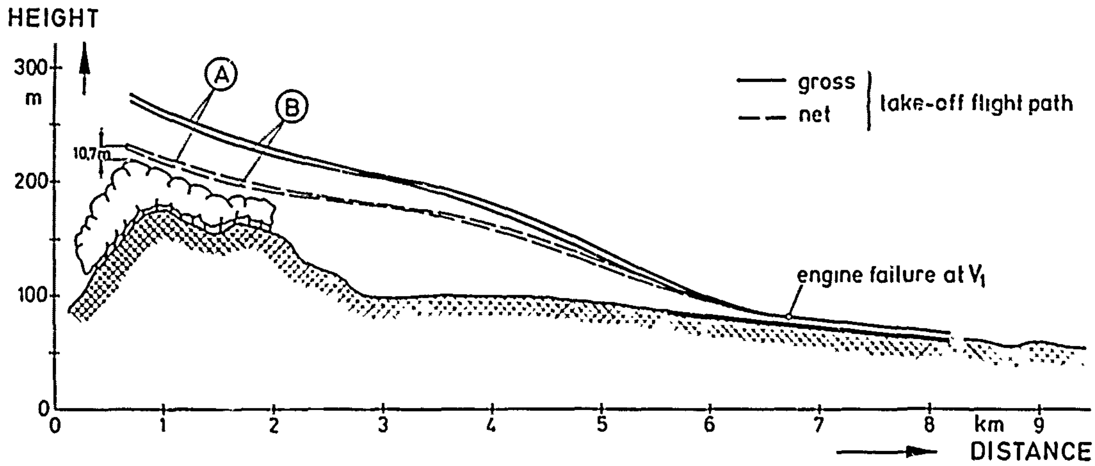

Fig. 16: Takeoff flight paths of two different aircraft in wind shear conditions on the lee side of a mountain ridge [3]

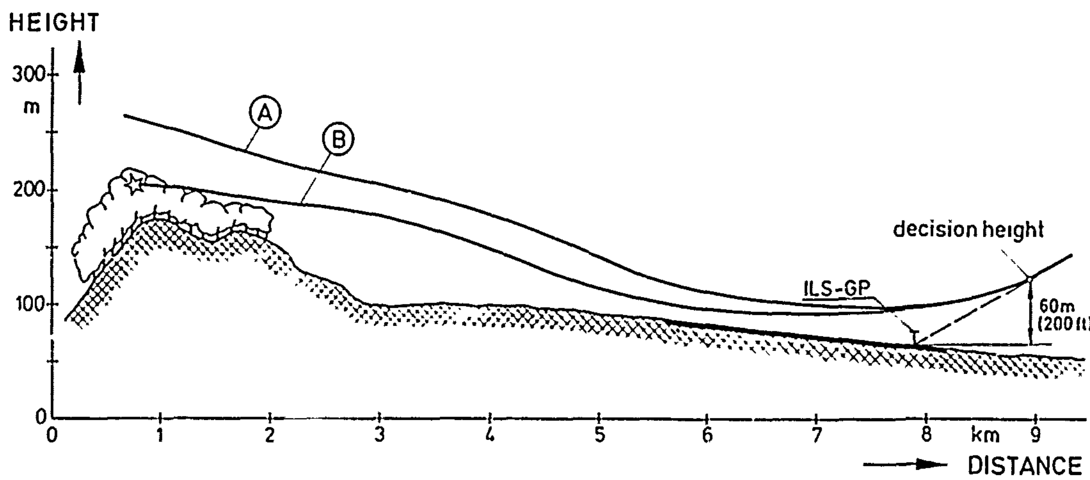

Fig. 17: Go-around flight paths of two different aircraft in wind shear conditions on the lee side of a mountain ridge [3]

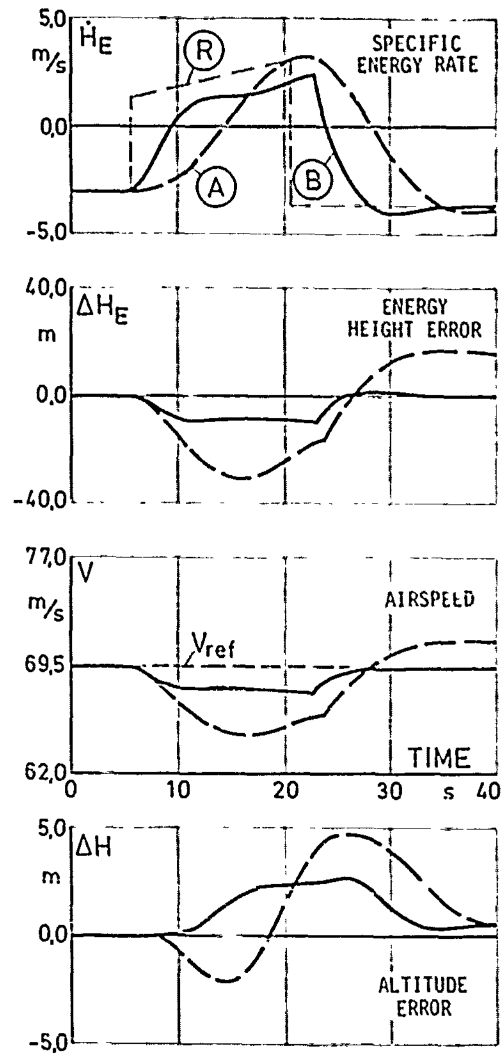

Fig. 18: Effects of flight controls activity in linear tailwind shear.
R: Required specific energy rate
A: Conventional automatic flight controls
B: Specific energy rate mangagement

51 Titles

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